PV Generation Capacity Reserve for Intermittency Mitigation and Revenue Maximization

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***Abstract*-- Over the last twenty years the major cost of Photovoltaic installations was attributed to the PV panels themselves. The recent growth in installed PV generator units led to a rapid manufacturing cost decrease. Consequently, the lower PV panel prices alter the analogy between the PV panel and the Balance of System costs. At the same time the generous subsidies offered to Photovoltaic plant owners are being dramatically decreased. The aforementioned changes in technology and energy market stress the need to revisit how the PV plant components are chosen and dimensioned. This paper presents a method for aligning PV plant design to the current markets by introducing an unconventional generation sizing technique. The work also identifies ways that the initial PV plant design could address aspects such as generation intermittency or grid support services by means of a properly sized PV generation capacity reserve. Three financial metrics are used to assess the benefits in an example 3MW installation.**

***Index Terms*--intermittency mitigation, capacity reserve, photovoltaic, revenue optimization, LCoE, NPV, IRR.**

I. NOMENCLATURE

C_{panel}	Cost of panel (€/W)
DoD	Depth of discharge (%)
IRR	Internal rate of return (%)
LCoE	Levelised cost of Electricity (€ct/W)
NPV	Net present value (€)
R&D	Research and Development
O&M	Operation and Maintenance
BoS	Balance of System
EPC	Engineer, Procure, Contract

II. INTRODUCTION

OVER the last few decades the dynamic and changing character of PV industries has led to dramatic improvements and cost reductions of photovoltaic systems. The continuous advent of new PV technologies, such as thin-film modules in the market [1]-[2] and the streamlining of production processes have increased the competition improving the PV module performance and causing significant decrease in manufacturing costs and PV module prices. As shown in Fig.1, the PV module prices have followed a rapidly declining trend from 1980 to 2011, more specifically, they have dropped from 22 $/W in 1998 to 1.88 $/W in 2011 and as expected they will decline further due to the repercussions of the global economic crisis and the increasing presence of low cost Asian producers that strive to improve their market share in the global modules market.

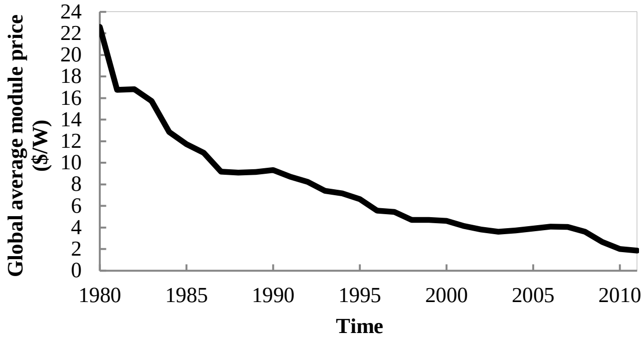

Figure 1: Global *average* PV module prices of all technologies during the period 1980-2011 [3] (Updated with data for the last two years from [4]-[5])

As a result, the current trend in utility scale photovoltaic installations is that PV generator cost reduces below 50% of the total investment cost. Balance of Systems (BoS) is accounting for the remaining cost of a photovoltaic investment. On the other side, the trends in PV electricity prices are equally remarkable. First of all, the non-existence of global PV prices is primarily due to the differences in energy yield of different areas that is related significantly to the site-specific solar irradiation and temperature levels. Secondly, the scale of the PV system plays an important role in the generated electricity cost as illustrated in Fig 2 (this work only considers the utility-scale systems). As shown in the figure it is anticipated that the PV generated electricity cost will continue to show declining trends unlike the wholesale and retail electricity costs that are expected to rise in response to the reduction of low cost highly polluting generation units such as coal-fired units. It is therefore expected that the utility-scale PV will achieve grid parity even earlier than 2020.

The authors of [6] describe a market scenario that assumes full grid-parity will be achieved in three phases: In the first decade the main reduction in PV generation will originate from PV panel price reductions by more than 50%. By 2020 PV generation costs are expected to decrease down to 7.5 €ct/kWh for utility-scale PV plants achieving grid parity with the retail electricity market in most countries. According to the authors between 2020-2030 PV utility systems generation costs will be 5-10 €ct/kWh. At this time

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most economic incentives for PV installations will be abolished whilst maintaining grid access guarantees and sustained R&D support. In the last phase the generation costs are expected to be as low as 3-7 €ct/kWh for PV utility systems.

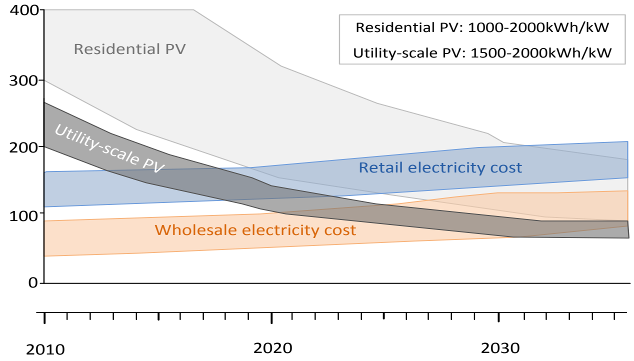

Figure 2: PV market deployment and competitiveness levels [6]

While PV modules will remain the single most costly part of a PV system in the foreseeable future, the large combined BOS costs will account for more than half the installed cost of a utility PV system, as can be seen in Fig.3. The work in [7] commented on the possibility for BOS cost-reduction and concludes that progress is unlikely to be as aggressive as it is for PV modules.

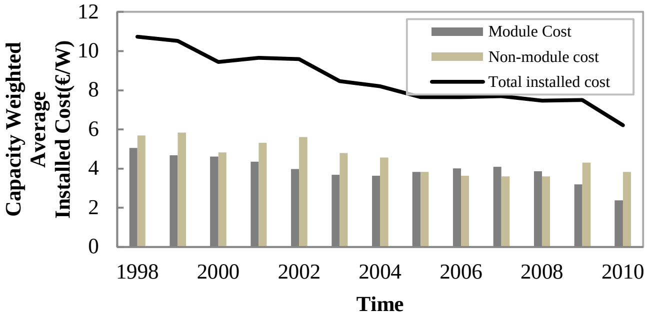

Figure 3: Module and non-module costs over time [7]

The above makes it clear that changing markets will impact the weights applied when engineering a PV plant solution. Apart from the markets themselves some new technical challenges arise as penetration of solar PV power increases locally and overall across the electrical grids. One such issue originates from the intermittent nature of PV generation; the same PV plant has a different generation output based on the particular irradiation profile of a day (Figure 4). In the examples shown the power available in the middle of a cloudy day can drop by more than 70% for several minutes. This will have multiple cost implications in the grid not only due to the power lost during this this short time but also due to the standby generation (e.g. gas stations) that will cover for this. As a consequence grid instabilities, inefficient transmission systems and additional costs hinder utility-scale PV generation expansion.

III. PV Generation Sizing

Given the cost and efficiency considerations of the PV panels and BoS, properly sizing the plant components becomes a critical design aspect. Traditionally, sizing of the PV system inverter is done based on the PV generator P_{GF} power and a sizing factor SF that typically ranges from 0.8 to 1.2% [8].

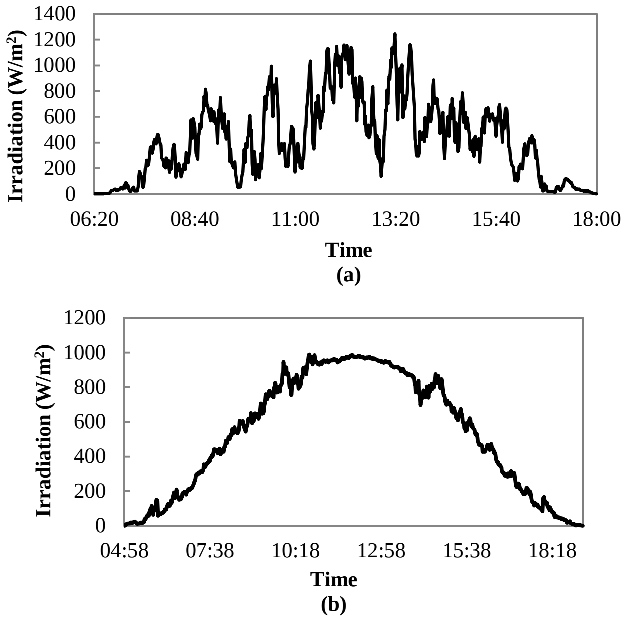

Figure 4: Irradiation data during two days in Catania (a) cloudy day of March (b) sunny day of July

$$P_{INV} = SF \times P_{GF} \quad (1)$$

There is no universal way of selecting the exact sizing factor hence some system integrators prefer to under-utilise the inverter to achieve a longer life of the equipment and possibly lower production loss due to inverter cut-out during irradiation peaks. Other designers over-size the inverter in the hope to convert every unit of energy given by the PV panels even at very low temperatures when they yield maximum power. There are different approaches such as that of the authors of [9] and [10] that propose an inverter undersizing by a factor as low as 0.6.

Additionally, it should be noted that most commercial inverter systems are optimized for operating at maximum efficiency near their full power operating point. As a result it is beneficial to operate the inverters at full power for as many sun-hours as possible.

Despite the different approaches there is a common practice among EPC integrators: they use the minimum possible number of PV panels in order to save in capital costs.

This has been a sound practice until very recently when PV panel cost dominated the investment cost. However, as PV panel cost decreases rapidly, the generation of electrical power tends to become more economic than processing it and feeding it to the grid.

The calculation of optimum size of PV generation should be based on appropriate metrics. In this particular method some key financial metrics are used to assess the benefit of installing a generation capacity reserve. Those metrics are introduced in the following paragraph.

IV. Performance Metrics

The key financial metrics that are used by banks and markets to assess the performance of a Photovoltaic generation project are:

- NPV – Net Present Value

- LCoE – Levelised Cost of Electricity
- IRR – Internal Rate of Return

Net Present Value is a way to project the future value that a project will generate into the present time. It is calculated by discounting each year's differential cash flows of the project balance sheet and then summing all values.

$$NPV = \sum_{n=1}^{N} \frac{(Income - Expenses)}{(1+r)^n}$$

The NPV is commonly used to evaluate if a project would add or subtract value to the company. Despite being appreciated by the markets, NPV has the limitation that it is sensitive to economy conditions and hence using it to compare the technical performance various projects is not adequate.

LCoE on the other hand is more suitable for involving technology aspects into the project economics. It is calculated as the NPV of the total value of the life-cycle cost of a project divided by the amount of electricity generated over the system life.

$$LCoE = \frac{TIC + \sum_{n=1}^{N} \frac{TOC^n}{(1+r)^n} - \frac{Res.Value}{(1+r)^n}}{\sum_{n=1}^{N} \frac{Annual\,Yield(1-Deg.rate)^n}{(1+r)^n}}$$

The life-cycle cost comprises three main components the Technical Investement Cost (TIC), the Technical Operating Costs (TOC) and the Residual Value of the installation upon expiration of the guaranteed period of operation. The Annual Yield is used along with the system Degradation Rate to calculate the present value of the overall yield during the project time N (in years). It is clear that the Discount Factor r has a great impact on LCoE value and should be carefully selected. The significance of LCoE is that it allows a fair comparison among systems with different lifetime, different location and regard-less of energy market conditions. While it is a good metric for comparing different systems with each other, LCoE is inherently weak in comparing projects from the point of view of an investor. The latter requires the energy markets to be taken into account which explains why IRR is the metric of choice for most investors.

The Internal Rate of Return is used to measure the profitability of an investment. It is practically the effective rate at which an investment would pay back over the project lifetime. Or it can be regarded as the discount rate which would give zero NPV for the project. The term internal refers to the fact that the calculation does not take into account external factors such as the inflation, interest rates variations etc. In this work the IRR is calculated over the differential cash flow values of the project lifetime.

V. PV Capacity Reserve

This work proposes the use of a capacity reserve of solar generation (PV panels) that is sized based on technical-economical criteria. The capacity reserve contributes in:

- Improving the BoS components utilization by operating the plant at nearly full-power during most of the day.
- Improving the plant generation profile seen by the grid by utilizing the capacity reserve during short/low irradiation events (such as clouding)
- Allowing more generous performance guarantees to be offered by EPC contractors by reducing the risk of reduced yield.

Due to the probabilistic character of the environmental conditions the prediction of PV plant daily yield may only be based on historical data and statistics (in this paper, the irradiation data of the Italian town Catania from 2010 are used). In reconsidering the PV generator sizing problem the main objective is to maximize the investment yield over the plant's lifetime. A second objective could be minimizing the depreciation time of the investment.

Fig.5 illustrates the PV generator output power curves with respect to number of PV panels as compared to a fixed 3MW inverter and BoS rating. It is clear that a larger number of PV panels will operate the BoS closer to its rated power for a larger portion of time. Fig.6 illustrates the total revenue of such a 3MW plant with respect to PV generator size.

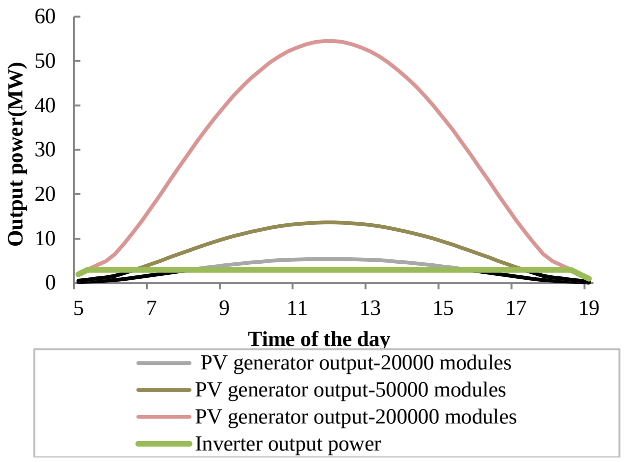

Figure 5: Installed PV generator output and inverter output power for various numbers of panels for at one sunny day of July in Catania.

Two electricity prices are considered; 400€/MWh is a strongly subsidised rate paid to PV electricity suppliers in certain markets (e.g. Southern Europe); and 200€/MWh is a more moderate market price (Central Europe). In a standard PV plant design a 3MW plant would require less than 10000 PV panels to produce the required peak power. It becomes clear from Fig.6 that there is a critical amount of PV generators that maximizes the plant revenue for a given BoS size and for different subsidies.

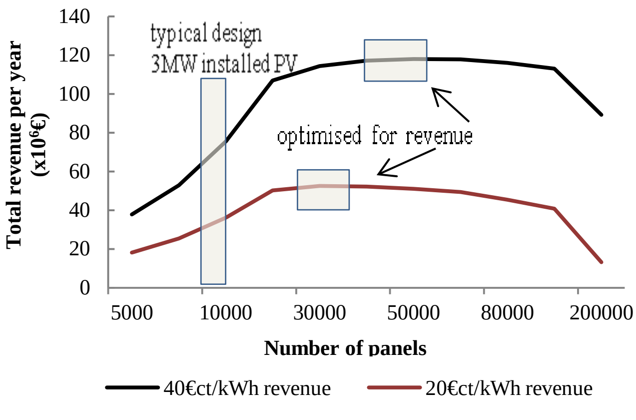

Figure 6: illustrates the number of panels and the total profit at the end of project life depending on the power selling price without taking into account the investment depreciation time. The gray shaded areas mark the conventional PV panel number selection and the optimized selection.

As shown, the power selling price affects the optimum number of panels so for 200 €/MWh, the optimal number of panels for maximum revenue is 35000-40000 while for 400 €/MWh is 50000-60000. However, as it will be pointed out in section V, the investment depreciation time for the above numbers is significantly higher, hence more analysis is required.

Another interesting aspect of the dimensioning of a PV generator is the intermittency of solar irradiation. At present, investors demand from plant manufacturers to predict a minimum return of the investment. This is clearly based on having accurate weather models for the area and being pragmatic about potential variations. Inaccurate predictions and poor performance imply heavy penalties for the plant manufacturers.

On the other end, the plant owners have to enter into energy trading agreements that include guarantees for minimum and maximum amounts of energy. A generation capacity reserve may be a reasonable measure for reducing the weather associated risks and reduce project costs such as unnecessary penalties. Fig.7 shows an example where an extreme high of generation capacity reserve of 44.1 MW (140000 modules x 315 W/module) is used on a cloudy day in Catania, Italy for a PV plant with an inverter rated at just 3 MW. It can be seen that in this ideal case clouding does not affect the plant output power.

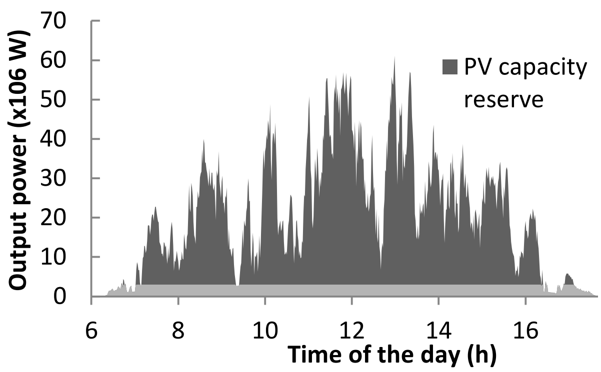

Figure 7: Generation capacity reserve during one cloudy day in Catania

Technically, power quality, grid stability and control can be improved and the plant may provide constant energy availability without interruptions and sudden changes in power flow [11]. Furthermore, the higher availability prevents potential variations of the grid voltage, hence reducing the risk of additional penalties for the violation of renewable source interconnection regulations [12]-[14].

As discussed earlier, the optimum number of panels is calculated so that the LCoE will be minimized and the IRR and NPV will be maximized, while the investment depreciation time is minimized. Using the weather time-series for the area of Catania, Italy in 2010 (PVGIS [15]) the problem is modeled in MATLAB 7.11.0 (R 2010b). Fig. 8 shows the LCoE for three different PV panel cost values with respect to the number of PV panels (normalized for the number of panels used in a typical design (3MW/315W=9523 in this case). The results are presented in the following section.

VI. RESULTS

Table I summarises the optimizing conditions for the three key investment metrics LCoE, IRR, NPV.

As can be seen in Fig.8, while the PV panel cost (€/Watt) decreases, the LCoE decreases and is, naturally, minimised for the minimum PV panel cost (0.4 €/Watt). However, the LCoE is not minimized when the smallest number of PV panels is used. This gives a clear indication that traditional methods for sizing the PV panel generator need to be reconsidered as PV panel market prices drop.

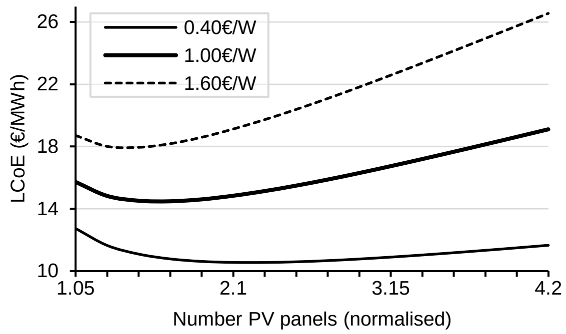

Figure 8: LCoE with respect to number of installed PV panels. The three lines represent different PV panel market price (€/Watt). The optimized LCoE points are indicated.

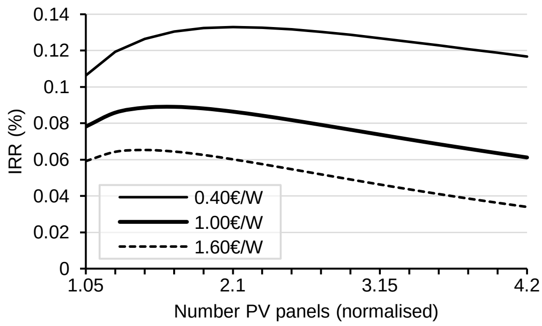

Figure 9: The IRR with respect to number of installed PV panels. The three lines represent different PV panel market price (€/Watt) and are calculated for an electricity market price increased at 200% baseline price .

The Internal Rate of Return shows a similar trend; lower PV panel prices require greater number of PV panels to obtain maximized IRR percent. The reason for this is that as the PV panel prices drop the project becomes less dependent on the upfront (capital) investment and the actual revenues play a more important role in maximizing the returns. This is illustrated in Fig.9.

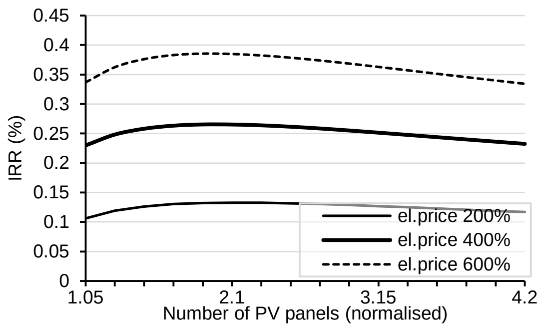

Figure 10: The IRR with respect to number of installed PV panels for three different incentivised electricity prices (200% to 600%) and a PV panel price of 0.4 €/Watt.

The effect of the incentives paid by governments is investigated by running the algorithm for 200% to 600% of a base electricity market price (5.5€ct/kWh). The results are illustrated in Fig.10. The IRR is naturally increasing while the electricity premium paid to producers increases.

It may be observed that, as far as IRR is concerned, higher incentives distort the project economics as they result in higher returns with smaller generation size.

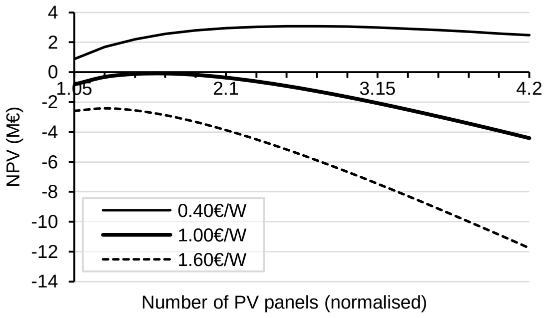

Figure 11: The NPV with respect to number of installed PV panels. The three lines represent different PV panel market price (€/Watt) and are calculated for an electricity market price increased at 200% baseline price.

Regarding the NPV of the project, the decreased PV panel prices clearly result in higher values. However, similar to the IRR trends lower PV panel prices make NPV less sensitive to the size of the PV generator and result in higher values with approximately twice the quantity of PV panels (20000). There is a point in PV generator size where adding more panels may not improve generation but only adds to the project costs (capital, maintenance). At this point the NPV starts decreasing again.

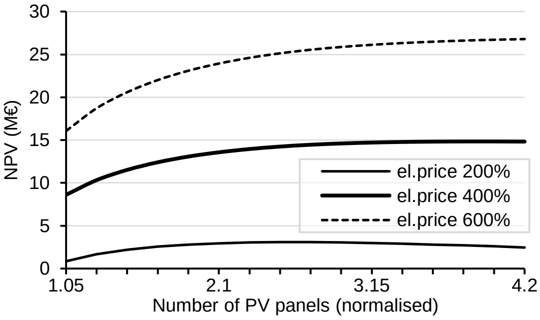

Figure 12: The NPV with respect to number of installed PV panels for three different incentivised electricity prices (200% to 600%) and a PV panel price of 0.4 €/Watt .

The market incentives do help in obtaining a higher project value and this is even more maximized if the number of panels is increased by 2-2.5 times. Beyond this point no extra energy may be generated and the curves decline.

The three metrics are not optimum for the same number of panels. This is because metrics such as the IRR and NPV depend on market parameters such as electricity price whereas the LCoE only depends on the balance of system, generator costs, operation costs and the plant energy yield. On the contrary all metrics are optimised when panel price is minimum (0.4€/W). The project Net Present Value seems to have the highest dependence on the market electricity price as well as the revenue stream. Hence, NPV is optimized when greater numbers of PV panels are used.

Overall it can be concluded that in electricity markets where policy makers offer increased financial incentives to PV producers, the PV generator size required to turn the project profitable is smaller. This is despite the potential losses of revenues due to low insolation or the poor BoS utilisation. This is more the case with higher PV panel prices and will become less important as they decrease.

TABLE I
TOTAL CALCULATION RESULTS

	Electricity price	5.5 €ct/kWh	5.5 €ct/kWh
	Incentivised price	200%	600%
Optimum LcoE	LCoE value	0.106 €/kWh	0.106 €/kWh
	Number of panels	22000	22000
	panel price	0.4 €/W	0.4 €/W
Optimum IRR	IRR value	13.3%	38.5%
	Number of panels	20000	18000
	Panel price	0.4 €/W	0.4 €/W
Optimum NPV	Maximum value	3.08M	26.8M
	Number of panels	24000	40000
	Panel price	0.4 €/W	0.4 €/W

In the next part of this section three different business cases are examined and compared using weather data from Catania, Italy. In the first case, the simulated PV system consists of a PV inverter rated at 3MW and equally rated PV generators. The following cases concern PV systems with 20000 and 40000 panels (all of the cases assume a market electricity price which is 200% of the base electricity price, namely 5.5€ct/kWh, and a PV panel price of 0.4 €/W)

The graph in Fig. 13 shows that the investment depreciation time for a traditionally sized PV system with nearly 10000 PV panels is 9 years. This is already shown not to be an optimum case when low PV panel prices are assumed as the LCoE is as high as 0.131 €/kWh nearly 2.5€ct higher than the optimum configuration with 22000 panels. The IRR is low too at just 10.2% as can be seen in Table II.

The cash flow graph in Fig.14 represents the design case with 22000 panels. In this case there is an improvement of nearly 2 years in the depreciation time if compared with the previous case. Additionally, the IRR is 13.3% whereas the LCoE is reduced to the optimal value of 0.106€/kWh.

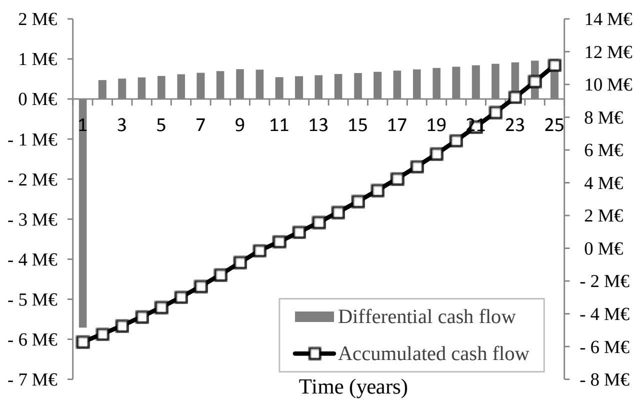

Figure 13: Accumulated and Differential Cash flows for a traditionally sized PV plant (with 9523 PV panels).

The depreciation time starts increasing as the PV generator size increases. This is because the accumulated cash flow may not grow faster due to the nearly full exploitation of the solar potential that has started already with fewer PV panels. As may be observed in Fig.15 the depreciation time is increased to more than 8 years and the LCoE has increased to 11.7€/kWh while the IRR has decreased to 11.7%.

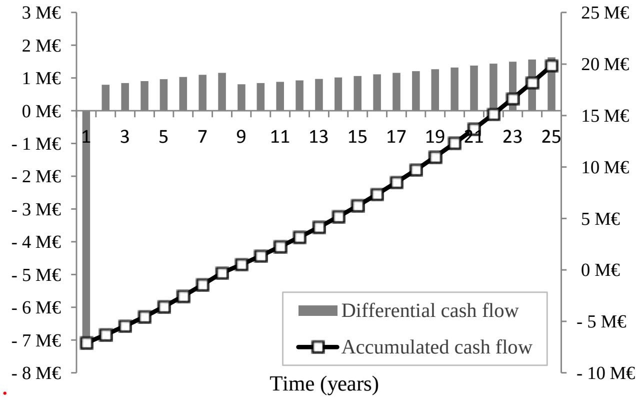

Figure 14: Accumulated and Differential Cash flows for the second PV system with 20000 panels optimizing IRR

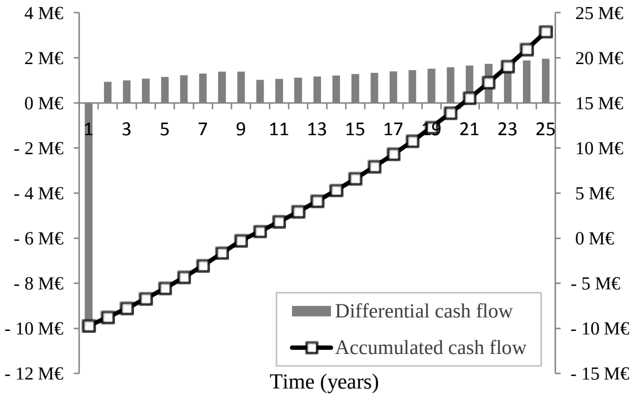

Figure 15: Accumulated and Differential Cash flows for the second PV system with 40000 panels optimizing NPV

Table II summarises the results of the above case studies.

TABLE II
FIGURES OF MERIT FOR AN INVESTMENT

PV Panels	9523	22000	40000
El Price	200%	200%	200%
Depreciation	9 yrs	7 yrs	8yrs
LcoE (€/kWh)	0.131	0.106	11.7
IRR	10.2%	13.3%	11.7%

The financial benefit of creating a PV generation capacity reserve has been demonstrated by the previous results. However, another significant advantage of the capacity reserve could be seen during periods of intermittent irradiation.

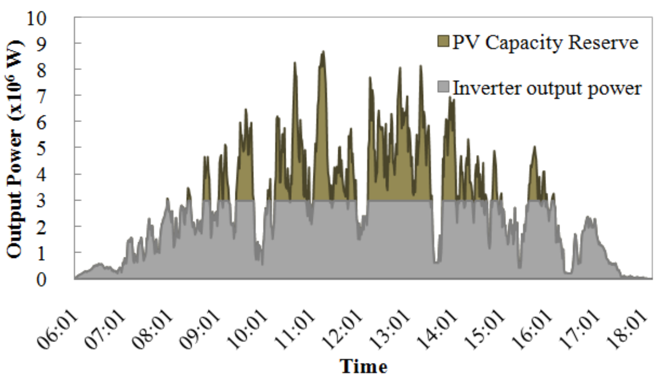

Figure 16: Loss of PV capacity reserve on a cloudy day of March in Catania using 22000 panels.

As shown in Fig.16, a PV plant BoS operates well under the rated power during a typical day in March. The fluctuations in the power of PV systems make it difficult to predict their output. The installation of a battery energy storage capacity in PV plants has been proposed in order to sustain the grid supply even when PV generation is lost or reduced. Battery energy systems are now a relatively mature technology [16], however the installation and operation costs tend to be prohibitive in particular with PV plants where the Levelised Cost of Electricity is already high. This is mainly due to the small lifetime of batteries and the frequent replacements needed [17].

The PV generation capacity reserve may be regarded as an energy storage replacement as it explores a radiation potential already in place (during clouding) that would otherwise remain unused. Using a generation reserve in the same way as a battery would allow reducing the cycling of a battery system during short intermittency events. This, in turn, would allow the battery to be used in baseload generation mode in which batteries demonstrate a longer lifetime expectancy.

VII. CONCLUSIONS

In this paper a new method of sizing PV plant generator was proposed after taking into account the trends in PV panel prices and electricity market prices. As the PV panel prices continue to follow a negative trend, the design emphasis shifts from PV panels to the Balance of System components and the Electricity Markets. The proposed method results in a revenue optimization by properly sizing the PV generator (number of PV panels). As the installed PV generator size increases beyond the inverter rated power a PV generation capacity reserve is created and the revenues from PV generation increase. An improvement of all figures of merit used in Solar PV project finances has been demonstrated by using nearly twice the number of PV panels used in a traditional design. The same capacity reserve operates partially as back-up power during irradiation intermittency events and hence the cycling of battery systems may be reduced.

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